Haptics: Science and Applications

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Guest lecture for EE 267
which sense is most valuable to you?

which would you relinquish last?
hap·tic ('hap-tik)
adj. Of or relating to the sense of touch.
[Greek haptikos, from haptesthai, to grasp, touch. (1890)]

Cutaneous
- Temperature
- Texture
- Slip
- Vibration
- Force

Kinesthesia
- Location/configuration
- Motion
- Force
- Compliance

The haptic senses work together with the motor control system to:
- Coordinate movement
- Enable perception

Johansson and Westling

J. Edward Colgate

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what would life be like without touch?

Cutaneous
https://www.youtube.com/watch?v=0LfJ3M3Kn80

Kinesthesia
http://www.youtube.com/watch?v=FKxyjfE83IQ
why do we have brains?

sea squirt

Daniel Wolpert

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how does your computer/smartphone/iPad see you?
tactual stereognosis

• Tactual = tactile = via the sense of touch

• Stereognosis = the mental perception of three-dimensionality by the senses, usually in reference to perceiving the form of solid objects by touch

• One study (Klatzky et al., 1985) showed that subjects could identify 100 common objects almost perfectly, taking about 2 seconds per object.

• People are very good at tactual stereognosis.
haptic exploratory procedures

Tactile Devices
Stimulate skin to create contact sensations

Hybrid Devices
Attempt to combine tactile and kinesthetic feedback

Kinesthetic Devices
Apply forces to guide or inhibit body movement
existing applications of haptics

entertainment

education

human-computer interfaces
human haptics: why do we study it?

• for science

• to cure diseases and deficits

• as engineers:
  • to make useful and effective haptic simulations
  • to set a limit of how good haptic simulations have to be (efficiency)
  • because haptic devices can be used in psychophysical/perceptual tests (an application of haptic technology)
types of haptic sensing

tactile
spatial form (SA I)
texture (SA I, PC)
movement (RA)
flutter (RA)
vibration (PC)

stereognosis
(SA I, Proprioceptors)

pain
pricking pain (A δ)
burning pain (C fiber)

temperature
cold (A δ)
warm (C fiber)

muscle force
(Golgi tendon organs)

body position/movement
(SA II, joint afferents, muscle spindles)
sensory homunculus

mapping the human somatosensory cortex
(Kandel, Schwartz and Jessel)
active vs. passive touch

• Active touch
  – Focus on the object

• Passive touch
  – Focus on the sensation experienced

• Try it

• Is active touch better?
  – *Purposiveness* vs. movement over skin
    – In 3D, yes

• How is this important to haptic device design?
mechanoreception
mechanoreceptive afferents

classified by depth:
I: closer to skin surface
II: deeper beneath surface

classified by rate of adaptation:
rapidly adapting = phasic
slowly adapting = tonic

classified by sending modality:
e.g., receptor structure
cross section of glabrous skin
Merkel (SA I)

- form and texture perception
- low-frequency vibrations

**Shape:** disk
**Location:** near border between epidermis & dermis
**Type:** SA I
**Best Frequencies:** 0.3-3 Hz
**Stimulus:** pressure
Ruffini (SA II)

Shape: many-branched fibers inside a roughly cylindrical capsule
Location: dermis
Type: SA II
Best Frequencies: 15-400 Hz
Stimulus: stretching of skin or movement of joints

• static and dynamic skin deformation
• skin stretch
Meissner (RA I)

**Shape:** stack of flattened cells, with a nerve fiber winding its way through

**Location:** in dermis just below epidermis

**Type:** RA I

**Best Frequencies:** 3-40 Hz

**Stimulus:** taps on skin

- motion, slip/grip
- dynamic skin deformation
Pacinian Corpuscle (PC / RA II)

**Shape:** layered capsule surrounding nerve fiber

**Location:** deep in skin

**Type:** PC

**Best Frequencies:** 10 to >500 Hz

**Stimulus:** rapid vibration

- high frequency vibration
- gross pressure changes
### cutaneous mechanoreceptors

<table>
<thead>
<tr>
<th>Receptor</th>
<th>Diam.</th>
<th>Density (Fibers/cm²)</th>
<th>Response</th>
<th>Percep. Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merkel</td>
<td>2mm</td>
<td>100</td>
<td>curvature</td>
<td>form &amp; texture</td>
</tr>
<tr>
<td>Meissner</td>
<td>5 mm</td>
<td>150</td>
<td>motion</td>
<td>motion &amp; grip control</td>
</tr>
<tr>
<td>Ruffini</td>
<td>8mm</td>
<td>20</td>
<td>stretch</td>
<td>hand shape, lateral force</td>
</tr>
<tr>
<td>Pacinian</td>
<td>Hand</td>
<td>20</td>
<td>vibration</td>
<td>tools &amp; probes</td>
</tr>
</tbody>
</table>
kinesthesia
kinesthetic sensing

perception of limb movement & position, **force**

- muscle receptors (muscle spindles and Golgi tendon organs)
- joint receptors (in capsules and ligaments of joints)
- skin receptors (slowly adapting cutaneous mechanoreceptors that measure skin stretch): Ruffini endings, Merkel Cells in hairy skin
force sensing

• Resolution 0.06 N
• Grasping force: 400 N!
• Which of the following objects weighs about one Newton?

automobile, Isaac Newton, bowling ball, baseball, a dime
proprioception

- derived from Latin, *proprius*, meaning “belonging to one's own self”
- in general, it provides a sense of static position and movement of the limbs and body in relation to one other and the world
- in much of the literature, proprioception is defined as the perception of positions and movements of the body segments in relation to each other (without aid of vision, touch, or the organs of equilibrium). This is in contrast to exteroception.
## Just Noticeable Differences at Joints

<table>
<thead>
<tr>
<th>Joint</th>
<th>Angular Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal-InterPhalangeal (PIP) Joint</td>
<td>~2.5°/*6.8°</td>
</tr>
<tr>
<td>MetaCarpalPhalangeal (MCP) Joint</td>
<td>~2.5°/*4.4°</td>
</tr>
<tr>
<td>Wrist</td>
<td>2.0°</td>
</tr>
<tr>
<td>Elbow</td>
<td>2.0°</td>
</tr>
<tr>
<td>Shoulder (front)</td>
<td>0.8°</td>
</tr>
<tr>
<td>Shoulder (side)</td>
<td>0.8°</td>
</tr>
</tbody>
</table>

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movement and position

threshold can depend on velocity and whether muscle is contracted

![Graph showing movement detection threshold vs. angular velocity for different elbow states.](image-url)

Index: 0.01 0.10 1.00 10.00 100.00

Angular velocity (deg/sec)

Movement detection threshold (deg)

- Index finger
- Elbow relaxed
- Elbow contracting

Jones, 2000

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While many tactile devices have been shown to improve performance during specific isolated tasks, the effect of tactile feedback on naive perception of mass, a percept that normally includes a kinesthetic component remains to be determined. The role of tactile feedback in mass perception is especially important since it has been suggested that humans integrate visual and haptic information in an optimal fashion, minimizing the variance in a final estimate by combining the two senses [4].

While some parameters can be estimated solely through visual feedback, mass requires haptic sensation because vision cannot be used to determine the density of objects. Though tactile feedback for perception of mass has been investigated with the aid of traditional kinesthetic devices [23], to the authors' knowledge, this work is the first direct investigation of virtual mass perception and other object physical properties when using a wearable skin deformation device.

HapTips have 3 purely translational degrees of freedom, making them particularly well suited for rendering forces that act in multiple directions during object manipulation, such as weight, friction, and stiffness. We performed two user studies to investigate how virtual objects are perceived with wearable fingertip skin deformation feedback. The results show that users can distinguish between virtual objects with different mass, and also how naive user perception of virtual object properties is affected when the mass, stiffness, or friction of the virtual objects is modified.

SYSTEM DESIGN

HapTips (Fig. 1) have two separate components. The first is a finger grounding interface that straps to the medial phalanx. Several sizes of this interface were created to enable use with participants of varying finger size. Grounding to the medial phalanx helps distribute forces from the tactor and results in a stimulus that feels like it originates from an external source. The interface holds a magnetic tracking sensor from an Ascension 3D Guidance trakSTAR system, which provides tracking information about the position and orientation of the fingers in free space at approximately 200 Hz.

The second component of HapTips is the delta mechanism, which attaches to the finger grounding interface via a dovetail feature. The delta mechanism moves in 3 DoF with a 10⇥10⇥5 mm workspace and has the ability to make and break contact with the fingerpad. It weighs approximately 32 g and is bounded by a box of size 21.5⇥48.8⇥40.2 mm. The position of the delta mechanism was controlled using a Sensoray 826 I/O board to output desired motor torques to linear current amplifiers. The bias springs in the base revolute joints provide mechanism torques in one direction, while the motors spool the tethers attached to the base links provide torques in the other direction. The mechanism is capable of up to 7.5 N of normal force and 2 N of lateral force. The delta mechanism joint torques were updated at approximately 3 kHz while the visual loop was updated at 100 Hz.

Virtual environments were created using CHAI3D [3], which uses the god-object algorithm [8] for determining dynamic object interaction forces. The neutral position of each HapTips tactor was set for each participant by moving the tactor into the fingerpad by approximately 0.5 mm. This initial offset normal to the fingerpad prevents the tactor from slipping laterally across the finger during use. During haptic rendering, the orientation of the HapTips in free space was used to transform the force vector of virtual interaction into the reference frame of the delta mechanism. The HapTips tactors were then commanded to move 1.58 mm/N from the neutral position in the vector direction of the virtual environment interaction forces, based on the mean lateral stiffness of the fingerpad [6].

The virtual environment and resulting interaction forces were updated at approximately 3 kHz. An Oculus DK2 was used to display the virtual environment to users. Participants wore noise canceling headphones playing white noise during the experiments. The system setup is shown in Fig. 2.
user

haptic device

motion and force signals

virtual environment
user

haptic device

motion and force signals

teleoperated robot
wearable and tactile haptics
Haptics for Robot-Assisted Surgery
Minimally Invasive Surgery

Surgeon

Instrument/Camera

Patient

Image source: www.womenssurgerygroup.com
Teleoperated Robot-Assisted Minimally Invasive Surgery

Surgeon → Master Console → Information-Enhanced Patient-Side Robot → Instrument/Camera → Patient

© 2013 Intuitive Surgical, Inc.
Da Vinci Surgical System (Intuitive Surgical)

patient-side robot

surgeon’s console
Force feedback: haptics and graphics

Jim Gwilliam and Mohsen Mahvash
Fingertip Haptics

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Skin stretch haptic device

Zhan Fan Quek, Sam Schorr, Ilana Nisky, William Provancher
Skin stretch haptic device
Mass Perception

When grasping and lifting a virtual object, users perform a virtual version of the manipulation of objects than proprioceptive afferents [15]. In contrast, tactile feedback devices can provide skin deformation feedback, which displays potentially more influential in exploratory procedures between the two types of deformation feedback, has been shown to provide effective precision of human perception of mass. We conducted a study to compare human perception of mass via kinesthetic feedback and tactile feedback in virtual and augmented reality environments. To provide compelling haptic interactions, a common task used for both manipulation and exploration of a virtual world, haptic (force and tactile) feedback is hypothesized to increase realism and task performance. A canonical task that cannot be achieved without the natural form of haptic feedback is the grasping and lifting of objects.

Our long-term goal is to understand how skin deformation and skin deformation feedback contribute to VR performance. We compare human perception of virtual mass via kinesthetic feedback and tactile feedback in both kinesthetic force feedback and for skin deformation feedback. We attempt to equalize their masses by the method of adjustments, which is the grasp and lift two virtual blocks and attempt to equalize their masses by the method of adjustments. From the transformation of soft tissues at the contact point when a hand comes in contact with an object, tactile afferents signal afferent responses (e.g., in Pacinian afferents) that occur when afferents [15] are influential in providing the virtual mass of two virtual objects computed from the lifting force overcomes gravity and the object lifts off the ground. This limits their range of motion due to the bulky and inconvenient to don/doff devices, are possible, but typically encumber exploration of a virtual world.

One form of tactile feedback is skin deformation feedback, which display potentially more influential in exploratory procedures between the two types of deformation feedback, has been shown to provide effective precision of human perception of mass. We conducted a study to compare human perception of virtual mass via kinesthetic feedback and tactile feedback in virtual and augmented reality environments. To provide compelling haptic interactions, a common task used for both manipulation and exploration of a virtual world, haptic (force and tactile) feedback is hypothesized to increase realism and task performance. A canonical task that cannot be achieved without the natural form of haptic feedback is the grasping and lifting of objects. Suchoski and Cole [17] show that update in a virtual environment that this interaction lacks realism without the natural form of haptic feedback.
Asymmetric Vibrations

Voicecoil (side) (a)
Voicecoil (end)
Magnet (b)
Electromagnetic Coil (c)
Rubber Membranes (d)

Skin Disp. (mm)
Time (s)

\[ f = 40 \text{ Hz} \ (t_1 = 7 \text{ ms}, \ t_2 = 25 \text{ ms}) \]

Heather Culbertson, Julie Walker, Michael Raitor
Reaction Wheels

Julie Walker, Michael Raitor, Heather Culbertson
Pneumatics

WRAP: Wearable, Restricted-Aperture Pneumatics for Haptic Guidance

Michael Raitor, Heather Culbertson, Julie Walker
Active Surfaces
Pin Arrays

Iwata et al. 2001

Leithinger et al. 2010

Velazquez et al. 2005

Follmer et al. 2013
Deformable Crusts

Mazzone et al. 2003  Mazzone et al. 2004  Klare et al. 2013

Particle Jamming

Brown et al. 2010

Cheng et al. 2012

Steltz et al. 2009
Haptic Jamming: Four-Cell Surface

Stanley, et al. 2013

Video is real time
Haptic Jamming Actuation

Stanley, et al. 2013
Haptic Jamming Actuation
Node Pinning
12-Cell Array

Pinning nodes allows greater shape output variability
Shape Simulation

Stanley and Okamura, 2016
Shape Simulation

Original 2D Image

Constructed 3D Data

Input into 3x4 Simulator

Output from 3x4 Simulator

Input into 6x8 Simulator

Output from 6x8 Simulator

Input into 9x12 Simulator

Output from 9x12 Simulator
Closed-Loop Control
100-Cell Array

100 cells
100-Cell Array

100 cells
100-Cell Array

Video is real time
Closed-Loop Control

Video is real time
Some envisioned applications

- Design
- Consumer
- Medical
- Assistive Technology
- Changeable Product
- Wearable!

Sean Follmer, Elliot Hawkes, Margaret Koehler, Nathan Usevitch
Encountered-Type Medical Simulator
Haptics for Education
Sequoia High School
Redwood City, CA

Warm Springs Elementary School
Fremont, CA
\[
\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = Q_j
\]
hapkit

http://hapkit.stanford.edu

Melisa Orta Martinez, Richard Davis, Tania Morimoto, Paulo Blikstein
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http://charm.stanford.edu